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Research Paper

Numerical study of the response of a group of energy piles under different combinations of thermo-mechanical loads

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A B S T R A C T

Energy piles are rapidly gaining acceptance around the world because they represent a renewable and clean source of energy that can be used for the heating and cooling of buildings, and the de-icing of infrastructures. This technology couples the structural role of pile foundations with an energy supply using the principle of shallow geothermal energy. The exploitation of geothermal energy represents an additional thermal load that is imposed to the foundation and the surrounding soil. Because the primary role of energy piles is the stability of the overlying structure, this aspect must be ensured even in the presence of the additional thermal load. This study summarises the results of 3-D thermo-hydro-mechanical finite element analyses that investigated the behaviour of a group of energy piles for which field data were available. This allowed the nearly unique validation of the numerical approach with experimental data and a confirmation of the reliability of the results. The work provides a summary of the foundation behaviour under both conventional and extreme thermal loading conditions with reference to a geothermal operation of the piles for cooling and/or thermal energy storage applications within one season. The interaction between the piles is studied and the thermally induced group effects analysed. Attention is dedicated to the vertical stress and displacement developments in the piles. The results presented in this study outline crucial aspects that may be considered by engineers for the geotechnical and structural designs of such geostructures.

1. Introduction

Energy piles are a relatively new technology that couples the structural role of classical pile foundations to that of heat exchangers to satisfy the energy needs of buildings and infrastructures. These foundations are equipped with absorber pipes embedded in the concrete that contain a heat carrier fluid that circulates and exchanges heat with the ground for heating and cooling. This process is particularly favourable because the temperature of the ground at depths of greater than a few meters remains relatively constant throughout the year, being warmer than the outside temperature during the winter and cooler in the summer. Geothermal heat pumps are connected to the pipes and can transfer the heat from the ground to the building and infrastructure during the winter, while they collect and inject the heat resulting from space conditioning into the soil during the summer. Because of this geothermal operation, energy piles are subjected to multi-source actions: thermal and mechanical loads. The effects of temperature changes on the response of these foundations represent an innovative challenge for geotechnical and structural engineers because they induce thermal expansion and contraction of both the piles and the surrounding soil as well as modifications of the stress state.

A fundamental understanding of this behaviour has recently been obtained for single energy piles through full-scale *in-situ* tests [1–3], model-scale experiments [4–9], numerical analyses [10–16], and the development of design tools [17]. A recent state-of-the-art review of the subject can be found in Laloui and Di Donna [18]. However, despite several recent numerical [11,19–21] and experimental [22–25] investigations, the response of groups of energy piles to thermo-mechanical actions is not yet completely understood.

Numerical techniques are powerful tools to study the behaviour of energy piles that are subjected to thermo-mechanical loads at both short- and long-term periods because they can consider a number of aspects governing the physical thermo-hydro-mechanical phenomena that are involved in the problem. For this reason, they can be employed to develop a theoretically- and scientifically-based framework to describe the geotechnical,

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structural, and energy performance of such foundations. However, the predictions of these models should ideally be checked with experimental results. The opportunity to have *in-situ* experimental data is rare, if not unique. In the context of the thermo-mechanical testing of full-scale energy piles, experimental campaigns require a full set of monitoring instrumentation, such as thermocouples, strain gauges, pressure cells and piezometers to be installed in a foundation as well as in the surrounding soil. A group of four energy piles that are part of the foundation of the recently-built Swiss Tech Convention Centre in Lausanne, Switzerland, was equipped with such instrumentation and experimental tests were performed by Mimouni and Laloui [24].

The study presented in this paper illustrates a 3D thermo-hydro-mechanical finite element model that reproduces the behaviour of this group of experimental energy piles. The numerical approach is first validated against the monitoring data [24] under the experimental conditions that are typical of the operational state of such a foundation and then used to investigate more extreme thermal loadings. The analyses refer to a geothermal operation of the piles for cooling and/or thermal energy storage applications within one season. The aim of the study is to increase the understanding of the thermo-mechanical behaviour of groups of energy piles to assess important aspects that may be considered for the geotechnical and structural designs of such foundations. The focus of the work is on the thermally-induced mechanical effects on the piles, while the interaction with the fluid flow in the pipes and the consequent energy aspects are not considered. This latter problem has recently been considered by Batini et al. [26].

In the following, the experimental site is described along with the experimental data that were used for the model validation. Next, the mathematical formulation and the constitutive models that were employed for the simulations and the characteristics of the finite element model are illustrated. The model predictions and the available *in-situ* experimental data referred to the operational state are then compared. Afterwards, the results of a series of additional numerical analyses referred to the extreme operational state are presented. Finally, crucial aspects that may be considered by engineers for the geotechnical and structural designs of groups of energy piles are presented.

2. The experimental campaign

The experimental site is located at the Swiss Federal Institute of Technology in Lausanne (EPFL) under the recently-built Swiss Tech Convention Centre (Fig. 1a) and was entirely developed by Mimouni and Laloui [24]. All of the experimental results presented in this paper and used to validate the numerical model are from these authors. The site includes a group of four piles that are equipped as energy piles and are connected to a heating mini-module that is designed for soil thermal response tests [27]. These piles are installed below the north-western corner of a heavily reinforced 0.9-m-thick raft that supports a 9×25 m^2 water retention tank (Fig. 1b). In addition to the four energy piles (labelled EP1, EP2, EP3 and EP4 in Fig. 1b), the foundation of the tank includes sixteen other conventional piles that are not equipped as heat exchangers. In plain view, the energy piles form a triangle within a 4.21 m square in which the central pile is located 3 m from each of the others. The piles, which were bored and cast onsite, are made of reinforced concrete and are 28 m long and 0.9 m in diameter. The groundwater table at the test site is at the top of the deposits. The soil stratigraphy is illustrated in Fig. 1c. The upper soil layer consists of alluvial soil that is 7.7 m thick. A sandy gravelly moraine layer is located below the upper layer from 7.7 to 15.7 m depth. A stiffer thin layer of bottom moraine is located from 15.7 to 19.2 m depth and lies on a strong sandstone. All of the piles were instrumented with strain gauges, optical fibres and thermocouples along their lengths as well as with pressure cells at their tips. Two soil profiles (S1 and S2; Fig. 1b) were also equipped with piezometers and thermistors. These instruments allow the thermo-hydro-mechanical response of the north-western corner of the foundation to be completely monitored.

The experimental program that was used to validate the numerical model consists of two tests, which are referred to as Test 1 and Test 2. Test 1 was performed before the construction of the water retention tank and involved the heating (and next passive cooling) of only the central pile (i.e., EP1 in Fig. 1b). The experimental configuration is shown in Fig. 2a. The goal of this test was to investigate the effect of temperature on the pile's mechanical behaviour under free head restraint conditions. Test 2 was performed after the construction of the water retention tank and involved the constant axial mechanical loads that were applied at the pile heads as shown in Fig. 2b. This experiment included four tests that were performed by heating each of the four piles separately (with a next passive cooling phase). Hereafter, these tests are referred to as Tests 2.*X*, with *X* being the number of the heated pile according to the labels indicated in Fig. 1b, i.e., Tests 2.1, 2.2, 2.3 and 2.4 (Fig. 2b). The goal of this second series of experiments was to analyse the thermo-mechanical behaviour of the energy foundation in terms of the thermal and mechanical interactions between the piles.

3. Mathematical model

The problem is represented by a reinforced concrete pile foundation that is subjected to vertical mechanical loads and is able to exchange heat with the surrounding ground. The soil is considered as a porous material, composed by a solid matrix and a fluid phase. The entire medium is considered to be fully saturated by water. Hence, three main aspects are involved in the problem: mechanical, thermal and hydraulic. These three aspects are coupled because the volume variations of the materials are affected by temperature, the heat exchange depends on the possible of groundwater flow, the water density varies with thermal loading and the mechanical response of the soil depends on the pore water pressure (effective stress concept). A fully-coupled thermo-hydro-mechanical formulation is therefore needed to exhaustively analyse the problem.

The Lagamine finite element software was used to perform the numerical analyses [28,29]. In this software, the equilibrium and balance equations as well as the water and heat diffusion laws are expressed in the moving current configuration through an updated Lagrangian formulation. In this paper, compression is positive.

Assuming Terzaghi's formulation for effective stress (hydro-mechanical coupling), the equilibrium equation is:

$$\nabla \cdot (\sigma'_{ij}) + \nabla p_w + \rho g_i = 0 \tag{1}$$

where $\nabla\cdot$ denotes the divergence operator, ∇ is the gradient, σ'_{ij} is the effective stress tensor, p_w is the pore water pressure, $\rho = n\rho_w + (1-n)\rho_s$ is the bulk density of the porous material, which includes the densities of water ρ_w and of solid particles ρ_s through the porosity n, and g_i is the gravity vector. The effective stress tensor is expressed in incremental form by introducing the constitutive models for each material (see below). The mass conservation equation is:

$$\partial_t p_w \left[n \frac{1}{K_w} + (1-n) \frac{1}{K_s} \right] + \partial_t T \left[n\beta'_w + (1-n)\beta'_s \right] + \nabla \cdot (v_{rw,i}) = 0 \tag{2}$$

where ∂_t represents the time derivative, the terms $\frac{1}{K_w}$ and $\frac{1}{K_s}$ are the compressibilities of the water and solid skeleton, respectively, T is